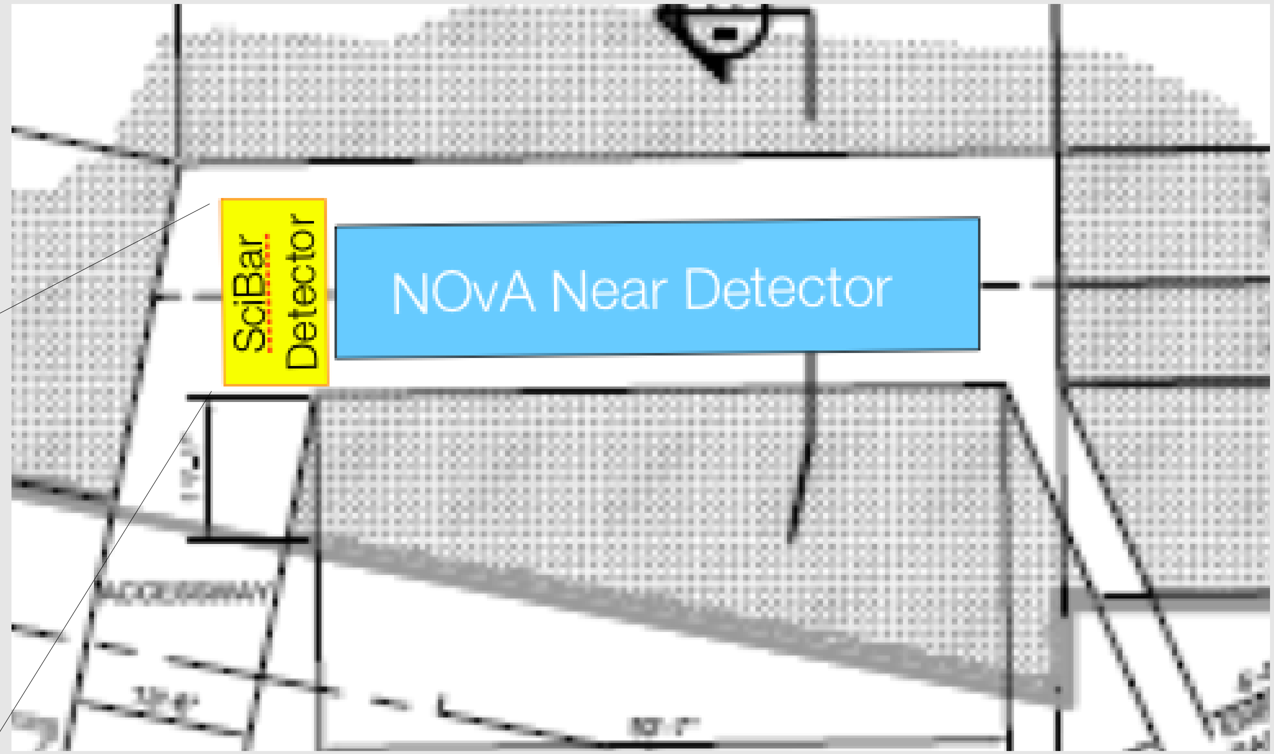
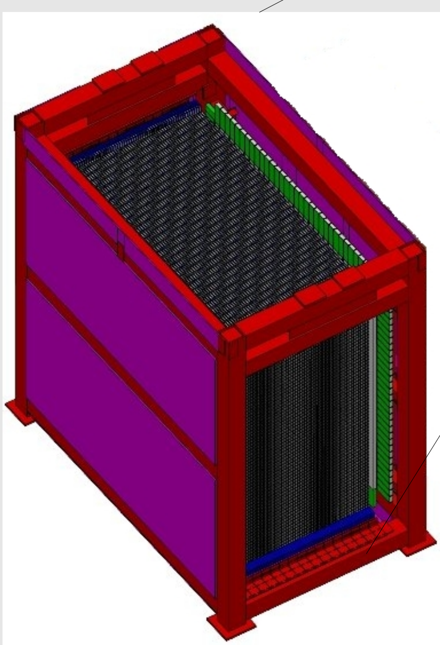
# SciNOvA: A Measurement of Neutrino-Nucleus Scattering in a Narrow-Band Beam

Outline:
- overview
- experiment
- science case:
  - ν scattering physics
  - NOvA oscillations
- status
- summary



R. Tayloe, Indiana U.
SBNW11
FNAL, 5/11

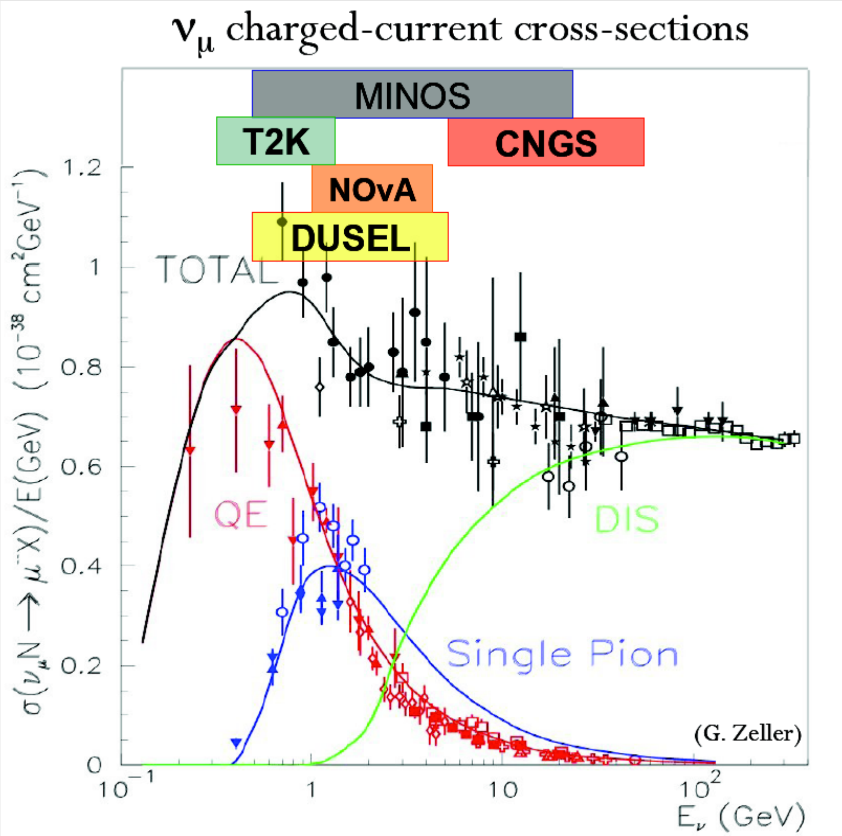
# Neutrino scattering measurements

In order to understand $\nu$ oscillations, it is crucial to understand the detailed physics of $\nu$ scattering (at 1-10 GeV)

- for NOvA as well as other experiments: MiniBooNE, T2K, LBNE
- especially for *precision* (e.g. 1%) measurements.

before MiniBooNE ~2000

Requires: Precise measurements to enable a complete theory valid over wide range of variables (reaction channel, energy, final state kinematics, nucleus, etc)




D. Schmitz, nufact'09

A significant challenge with neutrino experiments:

- non-monoenergetic beams
- large backgrounds
- nuclear scattering (bound nucleons)

SciNOvA, with narrow-band, 2 GeV, $\nu$ and $\bar{\nu}$ beams, would be ideally suited to contribute significantly.

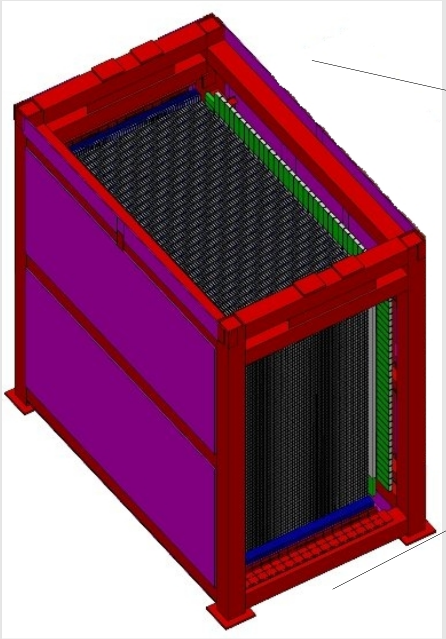
# Overview

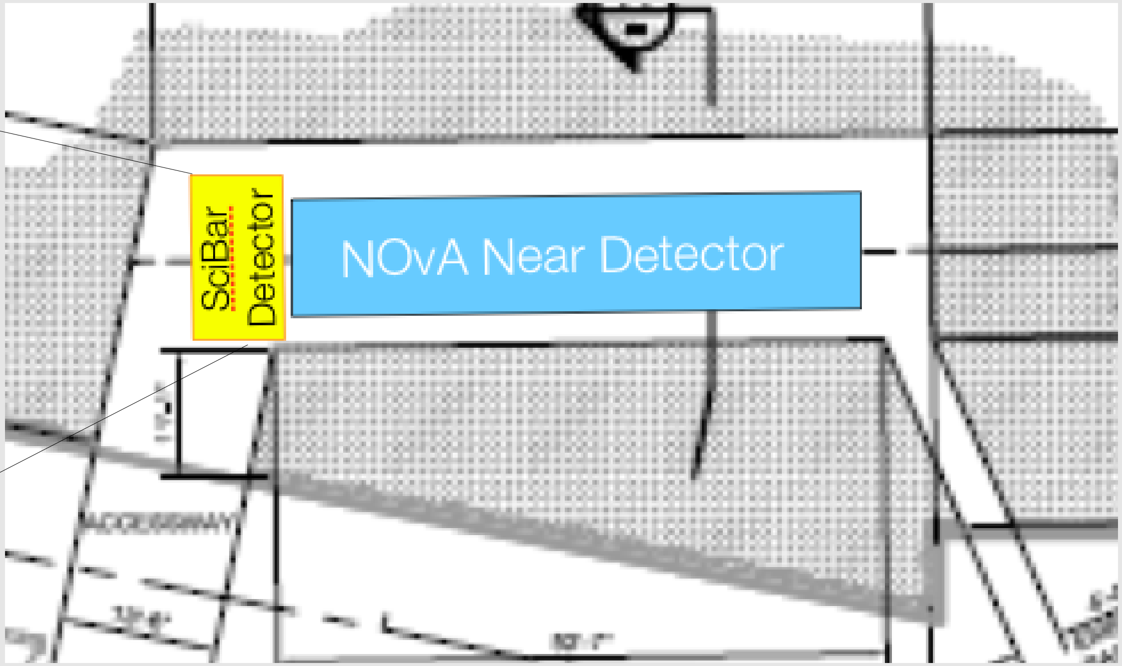
SciNOvA:

Build a SciBar detector using an existing and proven design (from KEK/SciBooNE), deploy in front of the NOvA near detector in the NuMI off-axis, 2 GeV, narrow-band beam.

A fine-grained SciBar detetor in this location will provide:

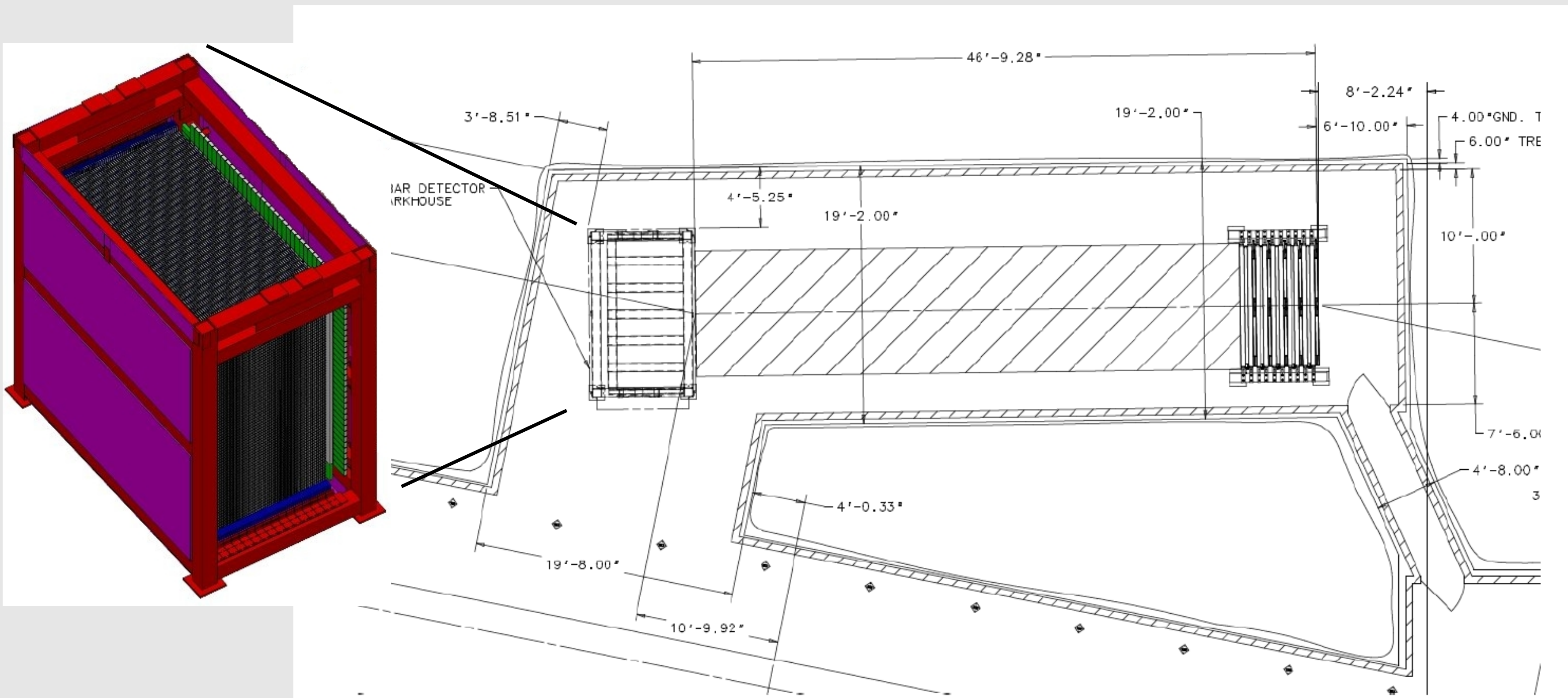
- important and unique $\nu$ scattering measurements including
  - a test of recent MiniBooNE results indicating anomalously large cross section in charged-current quasielastic scattering using a different $\nu$ source at slightly higher $E_\nu$
  - Neutral-current differential cross sections, $NC\pi^0$, $NC\gamma$ - crucial for $\nu_e$ appearance
- significant cross checks of NOvA $\nu$ oscillation backgrounds





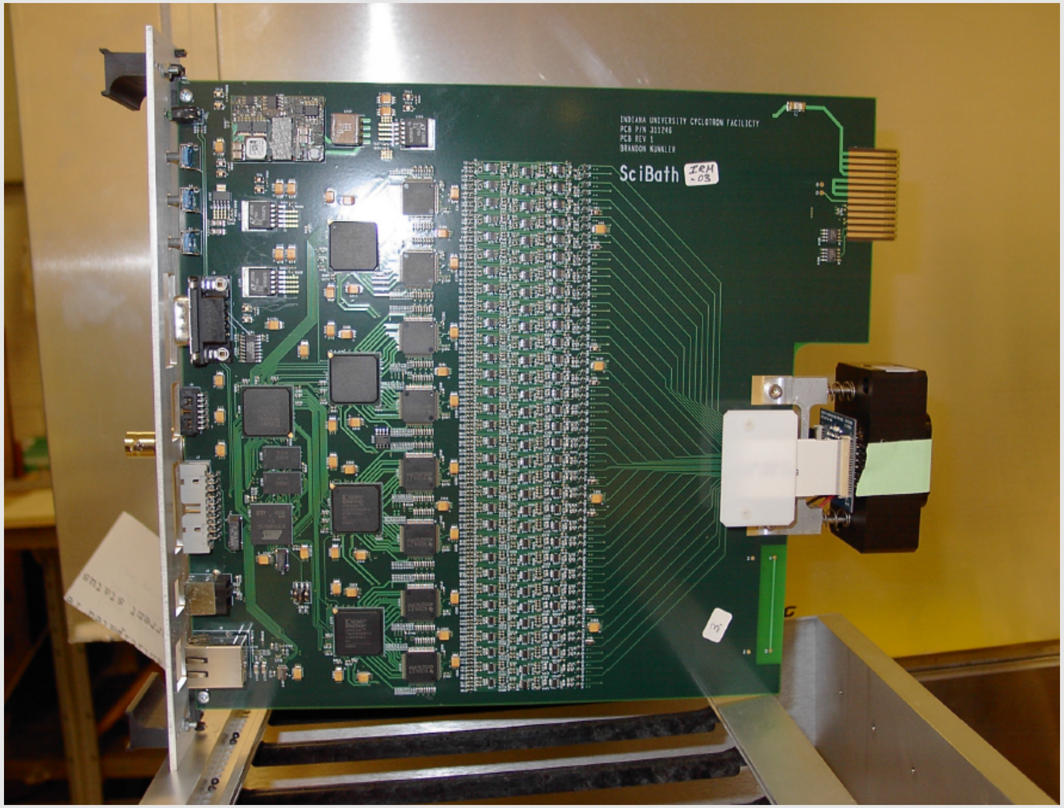
# SciNOvA detector

- 15k-channel solid scintillator SciBar detector in front of NOvA near detector
    - no cavern changes required, slight modifications to detector support structure
- (FNAL-made) scintillator extrusions (1.3cmx2.5cm), same design as existing SciBar
- 1.5mm WLS fibers into 64 anode PMTS
- readout system based on existing (and running) design (IU IRM modules)



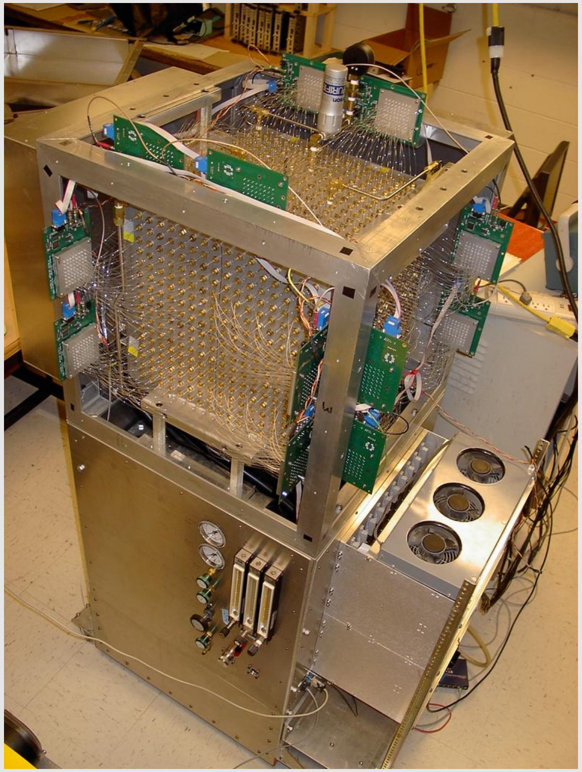
# SciNOvA detector

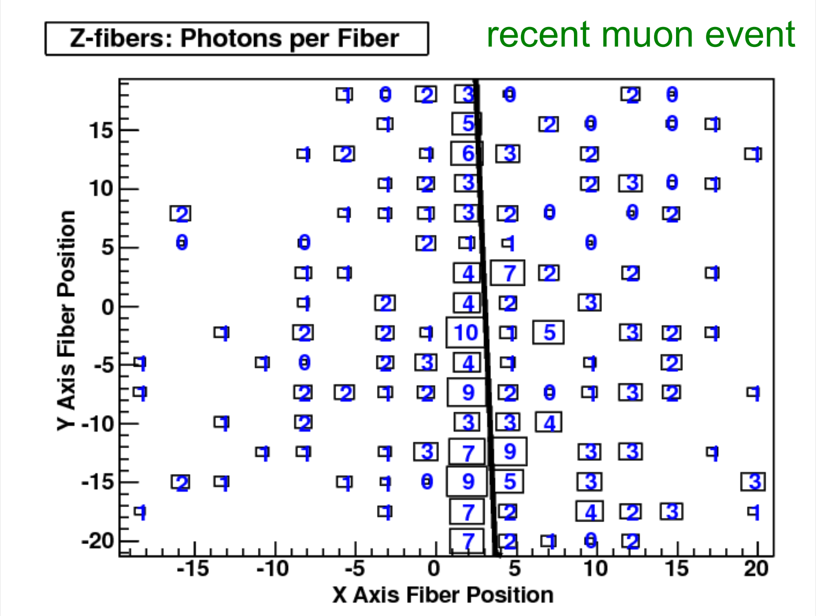
- (proposed) readout electronics:
  Integrated Readout Modules (IRMs) running now on "SciBath" detector at IU




IRM with attached PMT

SciBath detector






recent muon event

Scibath detector:
- WLS fiber/liquid scintillator (`100kg) for n/ν
- 12 64anode PMTs, 768 channels total
- testbeam run in MINOS this fall

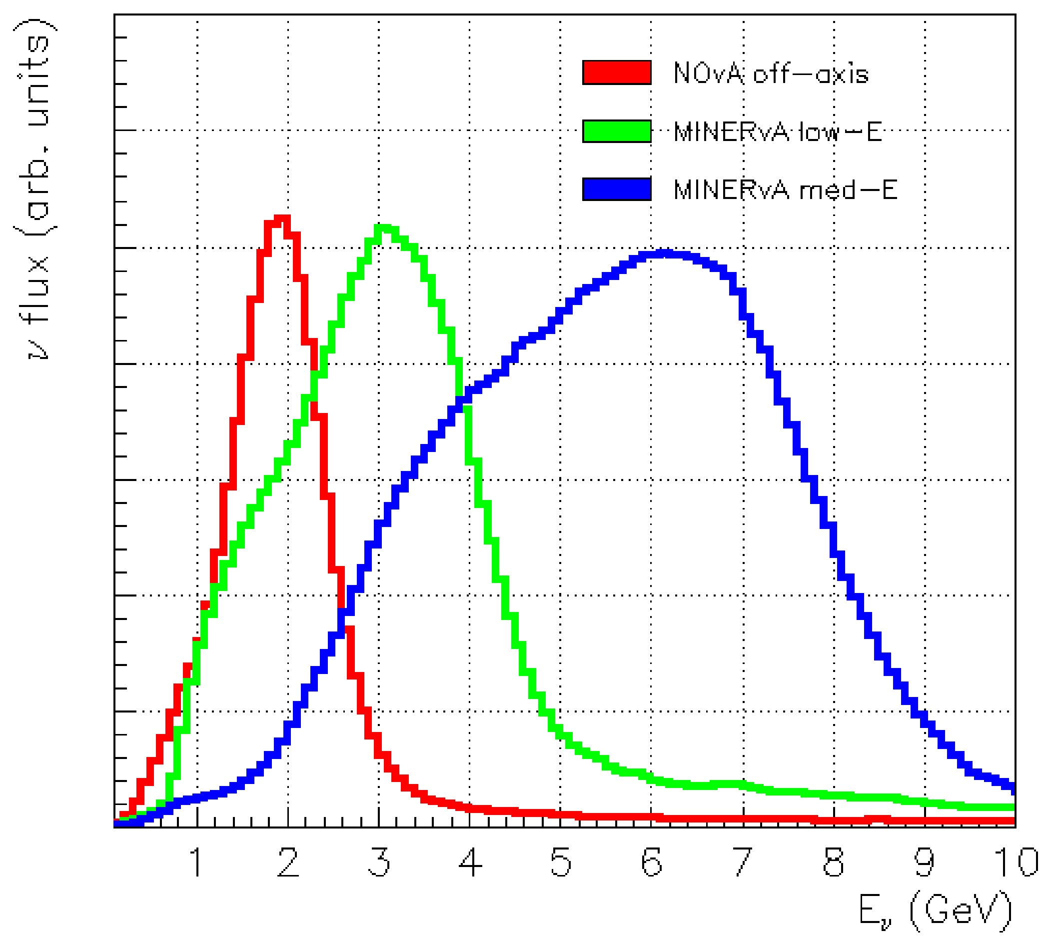
# Narrow band beam

- ~2 GeV mean energy,

- lower energy and smaller energy spread than on-axis flux

- complementary to the NUMI on-axis cross section program

NUMI ν fluxes



# Event rates

- High event rates in SciNOvA allowing measurements with excellent statistical precision.

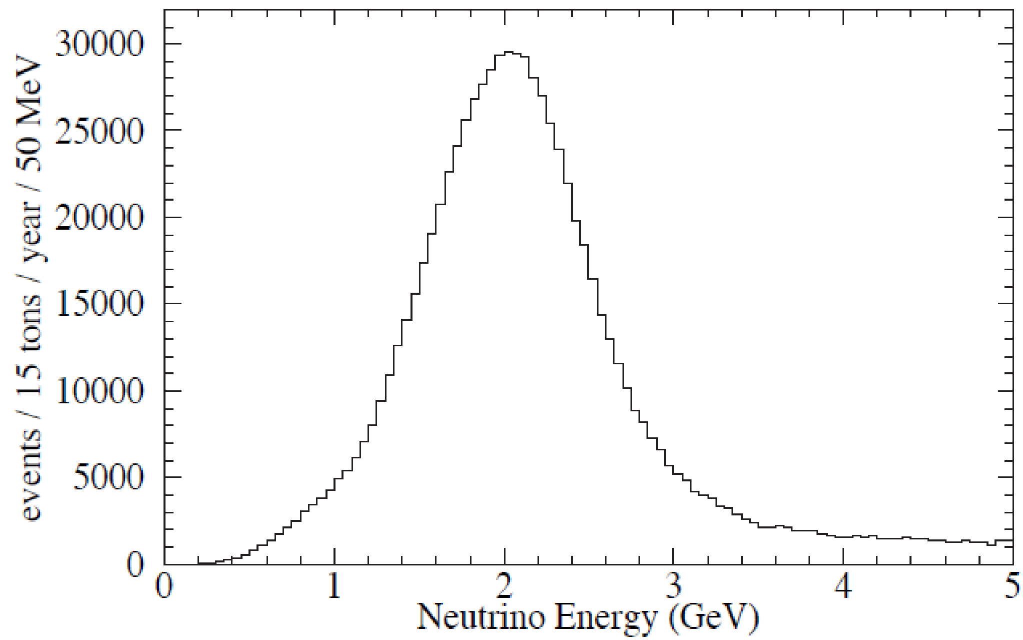
- Compare to MiniBooNE CCQE sample of ~150k events collected over 3yrs in 800ton detector.

- ~equivalent event sample collected in ~1 year with fine-grained detector

SciNOvA ν kevent/yr (6E20POT) in 10 ton fiducial vol

| | Charged-current | Neutral-current |
|---|---|---|
| elastic | 220 | 86 |
| resonant | 327 | 115 |
| DIS | 289 | 96 |
| coherent | 8 | 5 |
| total | 845 | 302 |
| $\nu + A \rightarrow \pi^0 + X$ | 204 | 106 |

energy distribution of events in SciNOvA



# CCQE scattering

MiniBooNE has recently pub'd results on various $\nu_\mu$ scattering channels, eg:

- CCQE, NC elastic, $CC\pi^+$, $CC\pi^0$

- In this data, (as well as for a few other experiments) the flux-averaged cross sections are O(30%) larger than state-of-art neutrino generator (with fermi-gas impulse approximation) predictions

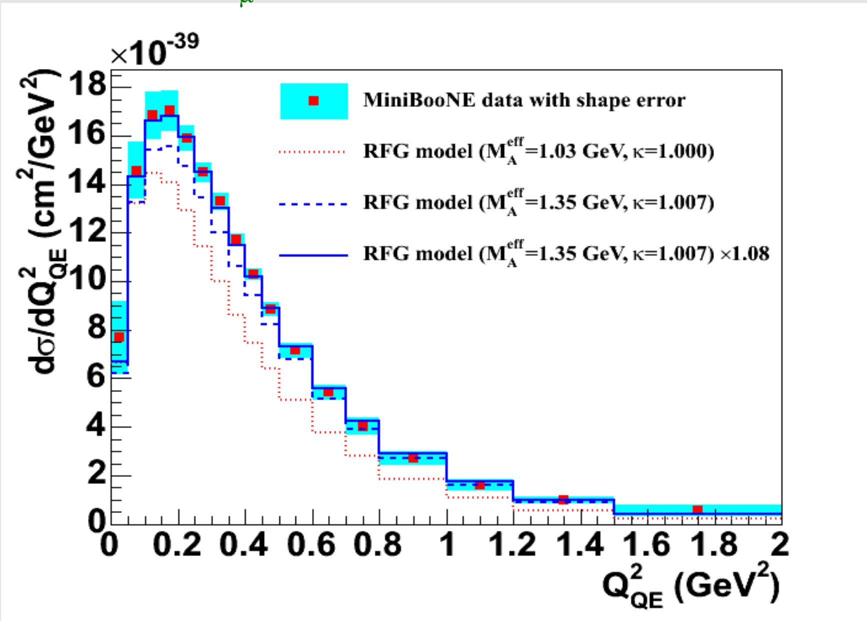
In particular, for the CCQE process.

This observation needs to be understood with additional measurements.

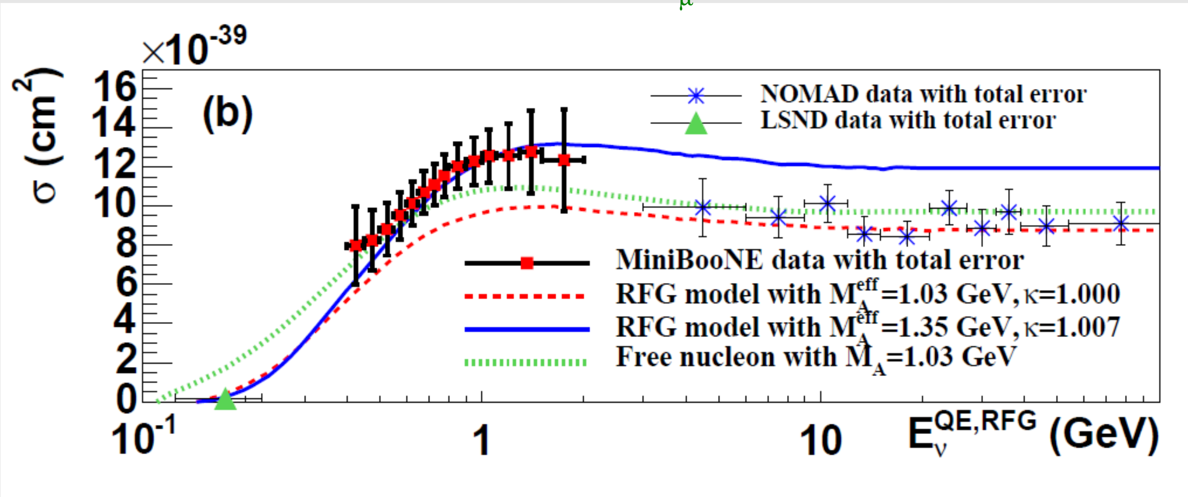
SciNOvA can provide this at 2GeV

complementary to MINERvA

MiniBooNE $\nu_\mu$ CCQE differential cross section




MiniBooNE $\nu_\mu$ CCQE total cross section



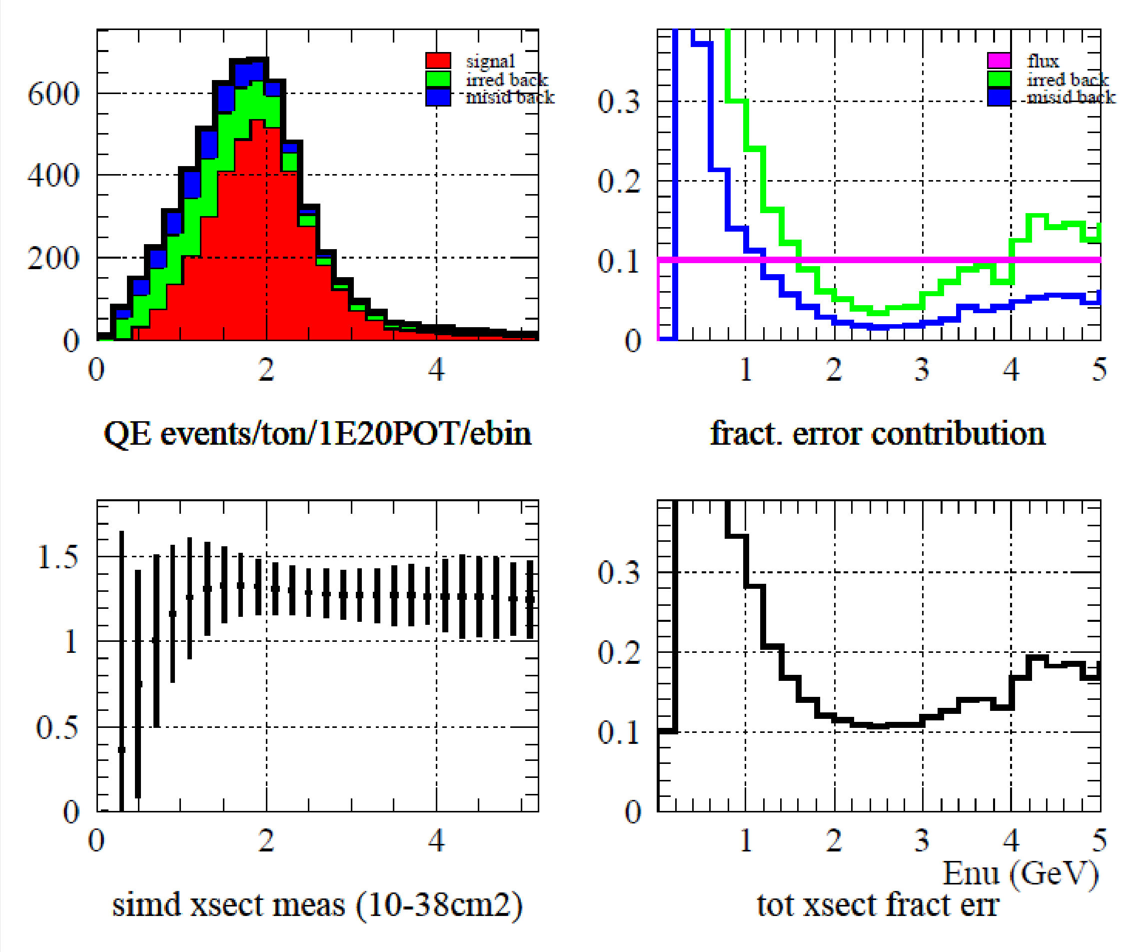
# CCQE scattering measurement

Estimated errors on SciNOvA CCQE total cross section measurement

- estimated with bootstrapping from MiniBooNE error analysis
- checked by predicting actual MiniBooNE errors
- dominant background is CC$\pi$ feeddown from high “true” $E_\nu$ to lower recon'd $E_\nu$ due to lost pion (in detector medium or nucleus)

- resulting error at 2 GeV (flux-peak of NOvA beam) is 12%

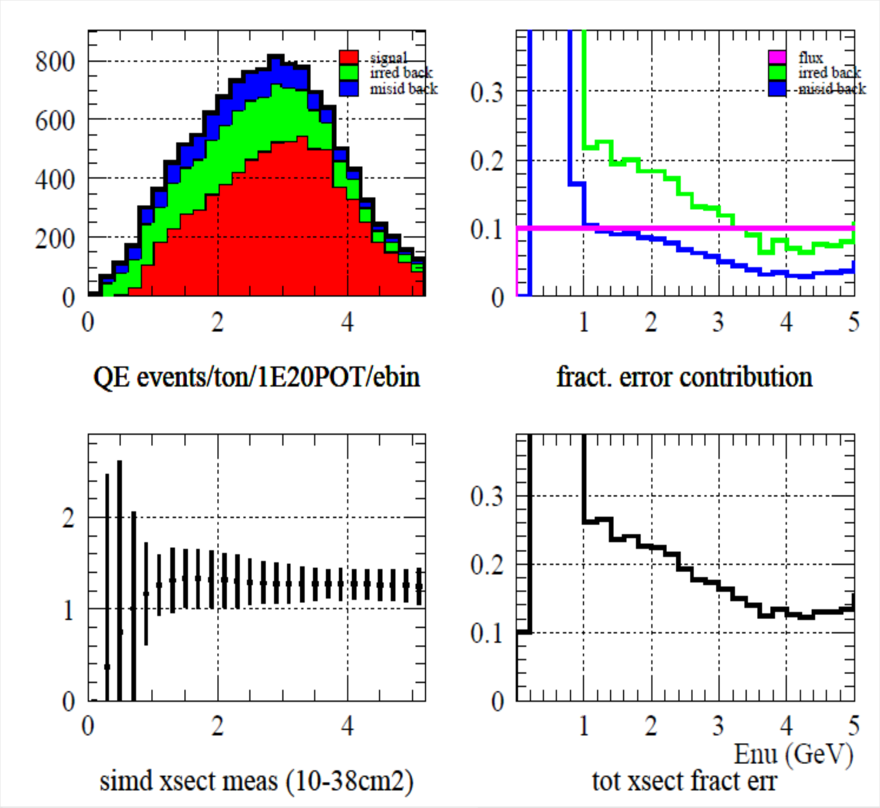
- will provide important points in CCQE total cross section data and most-directly check MiniBooNE results

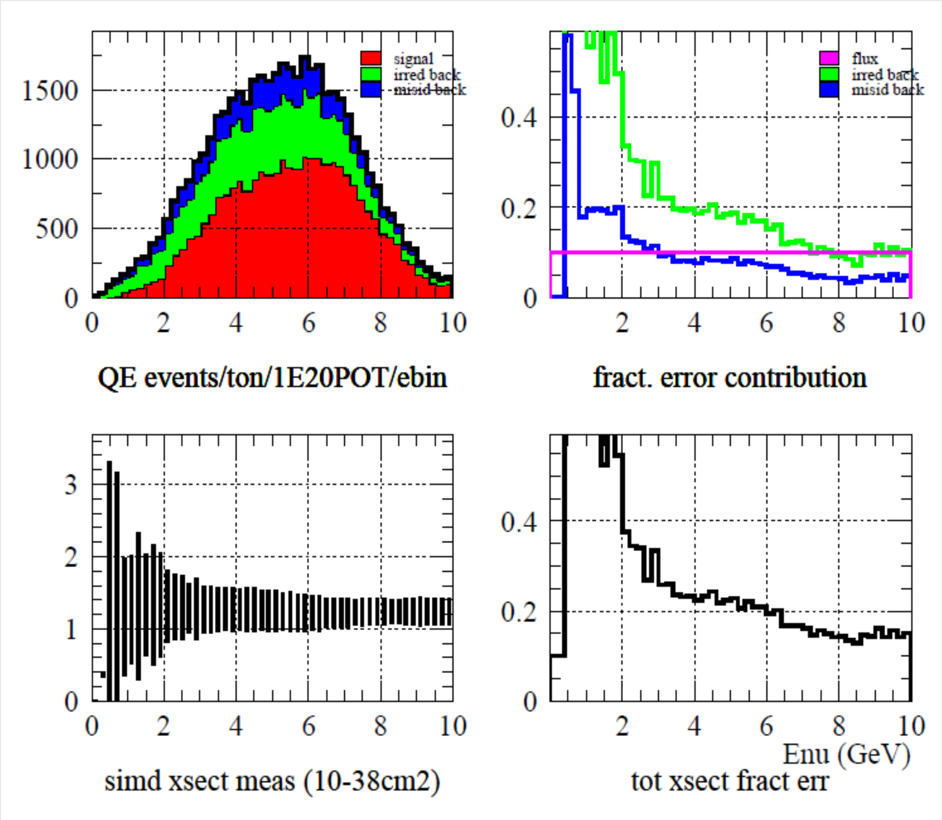



all plots as function of reconstructed $E_\nu$ (GeV)

# CCQE scattering measurement

Estimated errors on NUMI on-axis (low,med energy beam config) CCQE total cross section measurement, using same procedure:




all plots as function of reconstructed $E_\nu$ (GeV)

Estimated errors for CCQE cross section measurements at $E_\nu$ ~2 GeV in NUMI:

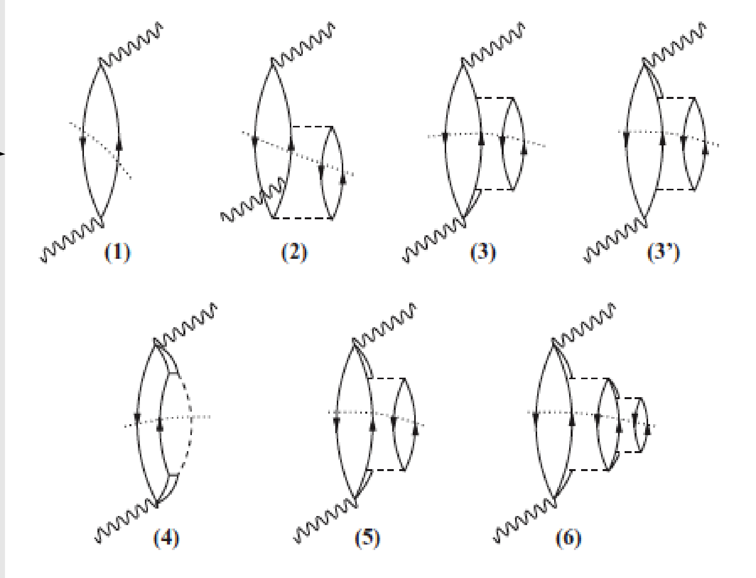
| NUMI flux config | total cross section estimated error (%) |
|---|---|
| 14mrad off-axis (SciNOvA) | 12 |
| on-axis, low-energy (MINERvA) | 23 |
| on-axis, medium-energy (MINERvA) | 35 |

# CCQE scattering and 2-N correlations

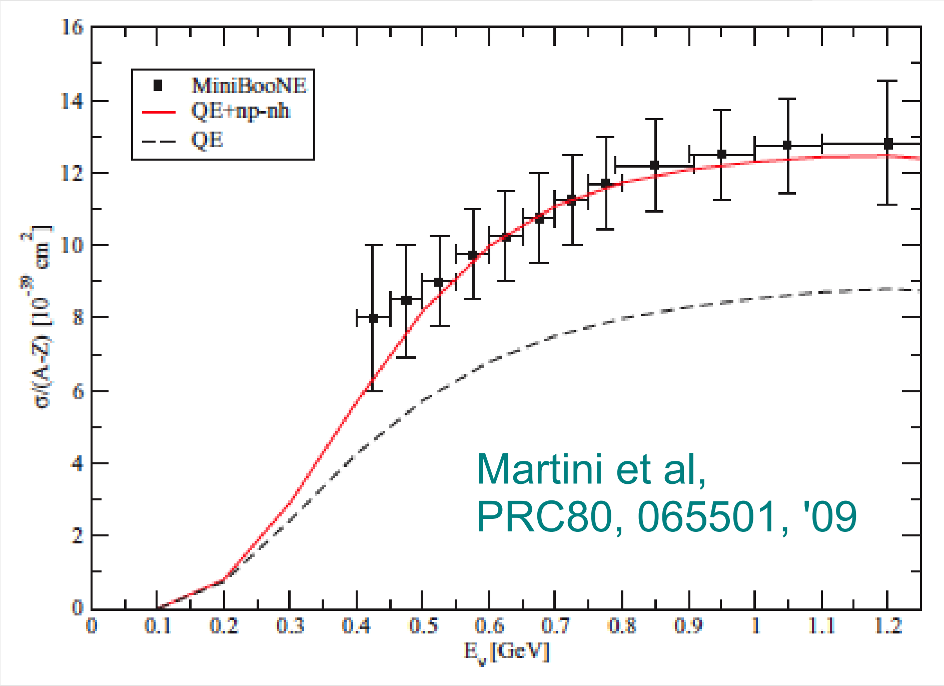
- Perhaps extra "strength" in CCQE from multi-nucleon correlations within carbon (Martini et al PRC80, 065501, '09)

- Related to neglected "transverse" response in noted in electron scattering? (Carlson etal, PRC65, 024002, '02)

- Expected with nucleon short range correlations (SRC) and 2-body exchange currents




CCQE total cross section



# CCQE scattering and 2-N correlations

- multi-N correlation idea is gaining theoretical momentum
- eg:" Pionic correlations and meson-exchange currents in two-particle emission induced by electron scattering", J.E. Amaro, etal, Phys.Rev. C82 (2010) 044601
- e-scattering calculation

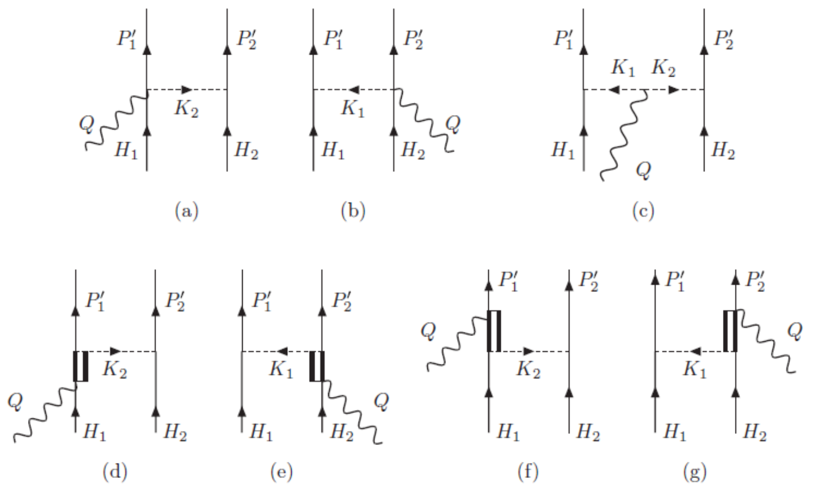



FIG. 1. MEC diagrams considered in the present study. Diagrams (a) and (b) correspond to the seagull, (c) to the pionic, and (d)–(g) to the $\Delta$ current, respectively.

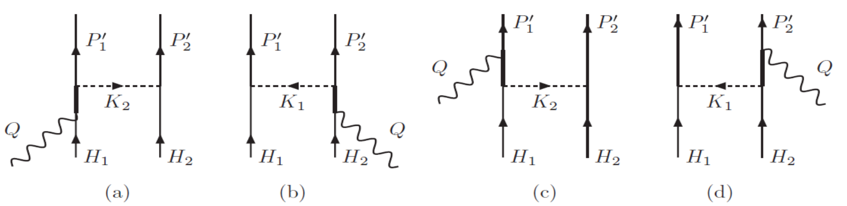



FIG. 2. Correlation diagrams considered in the present study. Diagrams (a) and (b) correspond to the forward, and (c) and (d) backward contributions, respectively.

predicted transverse response (on Fe)

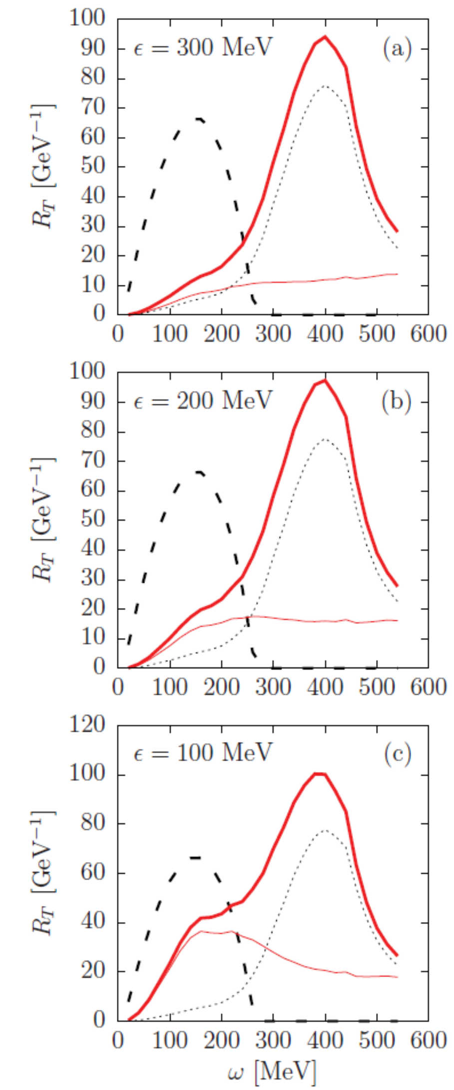
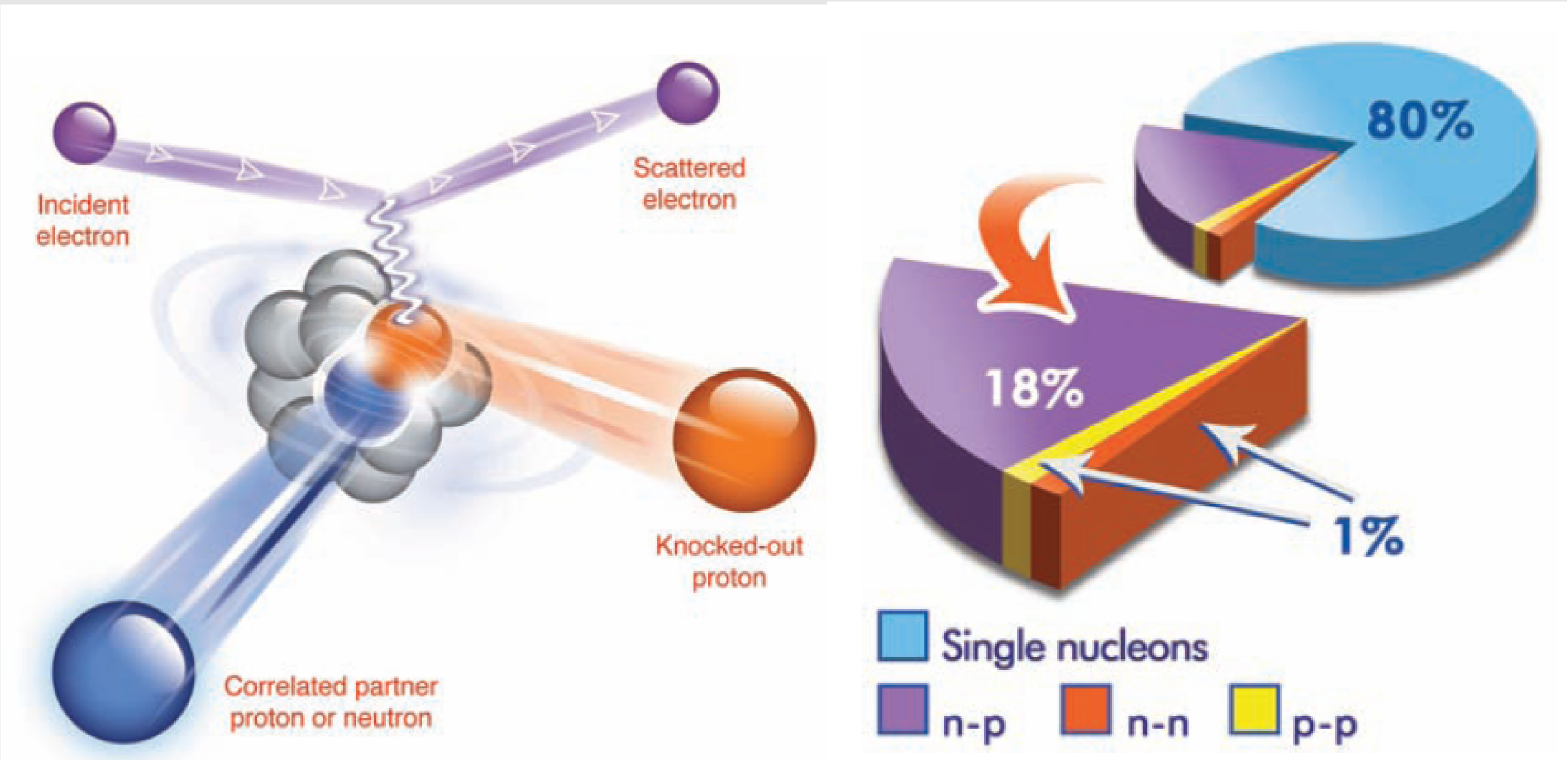



FIG. 3. (Color online) 2p-2h transverse response of $^{56}$Fe at $q = 550$ MeV/c. Three values of the parameter $\epsilon$ are shown. Thin solid lines, correlation only; dotted lines, MECs only; thick solid lines, total; dashed, RFG OB results.

# CCQE scattering and 2-N correlations

- Also, recent results from e-scattering suggest 20% of nucleons in carbon are in a “SRC state”

(R. Subedi etal, Science, 320, 1476 (2008))




This effect should result in distinguishable final states of multiple recoil nucleons.

Can be experimentally tested with SciNOvA.

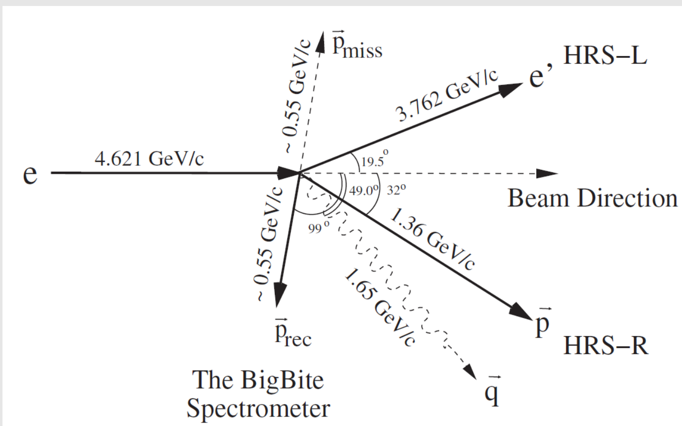
# Measuring 2-nucleon correlations

missing momentum plots

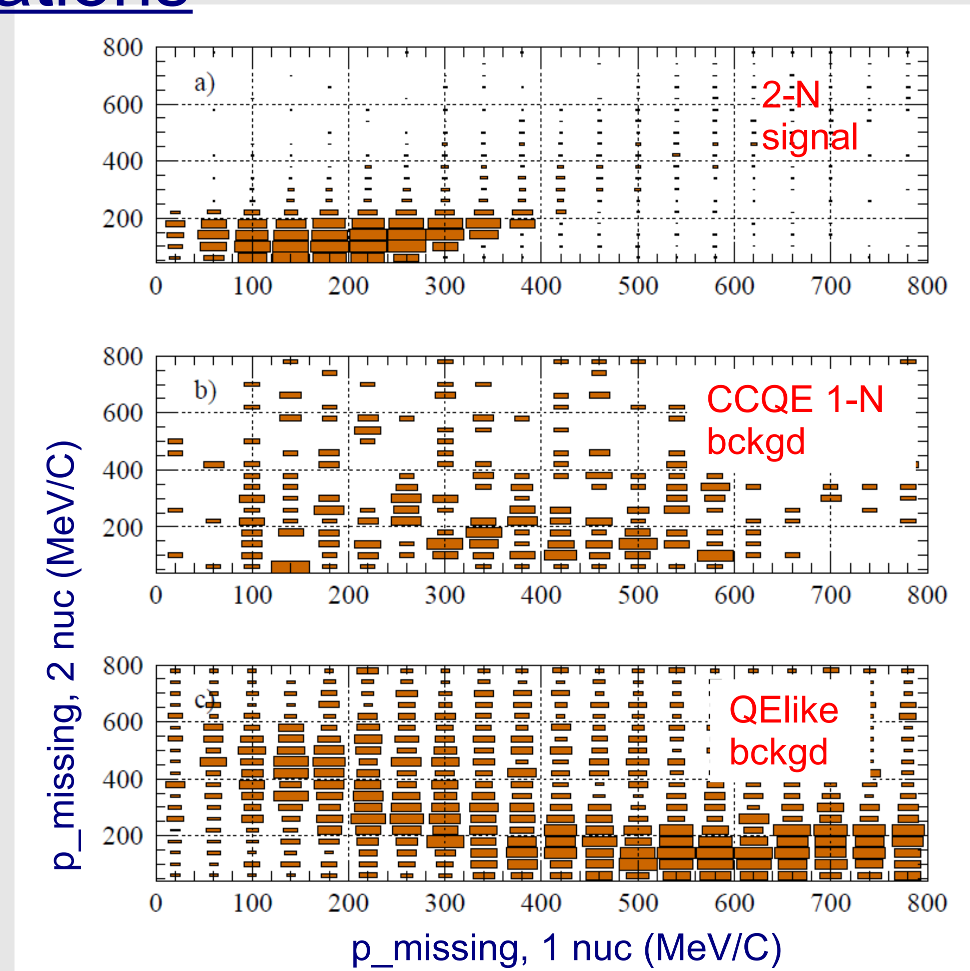
- A search for 2 nucleon correlations with SciNoVA is experimentally feasible and would provide the most direct test for MiniBooNE results.

Sketch of experimental method:

- Following method of JLab Hall A experiment:




- Find CCQE scattering events with 2 high-momentum recoil nucleons.
- Use transverse kinematics to eliminate neutrino energy unknown (all longnitudinal)
- look for transverse momentum balance when both nucleons considered.
- Separated from more mundane CCQE, CC$\pi$ events where energy should be shared with unobserved particles and recoil nucleus.
- Modeled with assumed extra 30% 2N events.

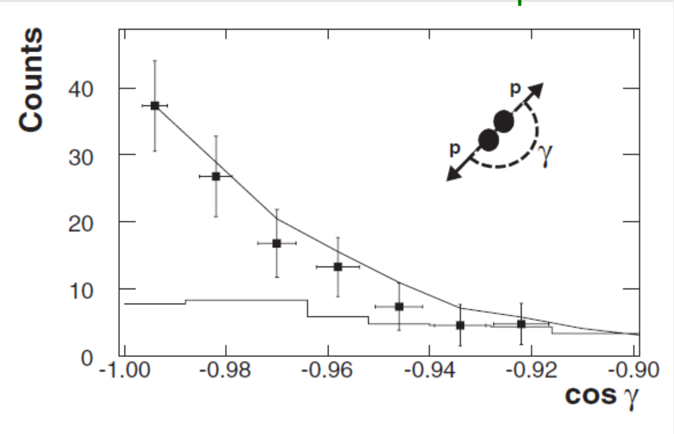


# Measuring 2-nucleon correlations

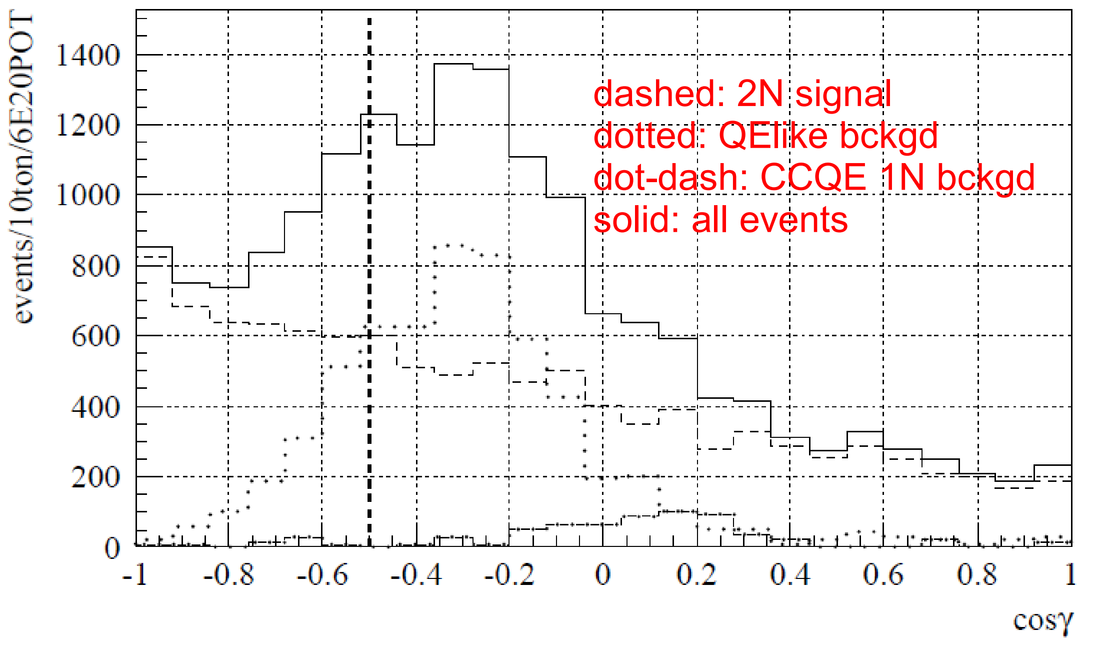
Experimental search with SciNOvA (continued)

- look at cos γ ,angle between 2 nucleons

from JLAB experiment




cos γ distribution




- Resulting, signal/background ~ 3...

- a sensitive search for this process

- and an important experimental constraint.

event totals past 2-N cuts

| event type | events/10ton/6E20 |
|---|---|
| 2-nucleon signal | 4119 |
| CCQE 1-nucleon background | 65 |
| QElike background | 1320 |
| total background | 1384 |

# NC photon production

- MiniBooNE low-energy excess has spurred work on a possible background: NC$\gamma$ production
- important background for $\nu_e$ appearance searches
- eg: R. Hill, Phys. Rev. D 81, 013008 (2010) and e-Print: arXiv:1002.4215 [hep-ph]

TABLE I: Single photon and other backgrounds for MiniBooNE $\nu$-mode in ranges of $E_{\mathrm{QE}}$. Ranges in square brackets are the result of applying a 20 – 30% efficiency correction.

| process | 200-300 | 300-475 | 475-1250 |
|---|---|---|---|
| $1\gamma$, non-$\Delta$ | 85[17 – 26] | 151[30, 45] | 159[32, 48] |
| $\Delta \to N\gamma$ | 170[34 – 51] | 394[79 – 118] | 285[57 – 86] |
| $\nu_\mu e \to \nu_\mu e$ | 14[2.7 – 4.1] | 20[4.0 – 5.9] | 40[7.9 – 12] |
| $\nu_e n \to ep$ | 100[20 – 30] | 303[61 – 91] | 1392[278 – 418] |
| MB excess | $45.2 \pm 26.0$ | $83.7 \pm 24.5$ | $22.1 \pm 35.7$ |
| MB $\Delta \to N\gamma$ | 19.5 | 47.5 | 19.4 |
| MB $\nu_\mu e \to \nu_\mu e$ | 6.1 | 4.3 | 6.4 |
| MB $\nu_e n \to ep$ | 19 | 62 | 249 |

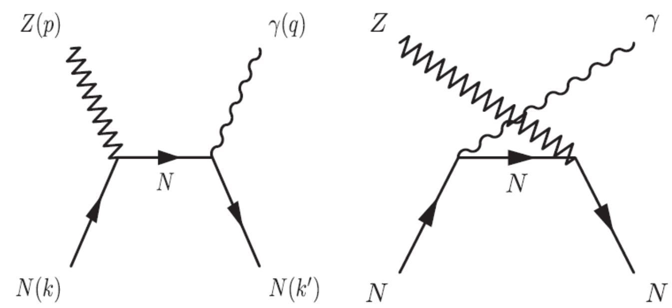



FIG. 1. Generalized Compton scattering.

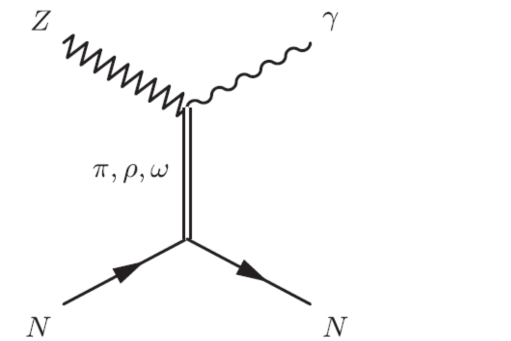



FIG. 2. Meson-exchange contribution to $Z^*N \to \gamma N$.

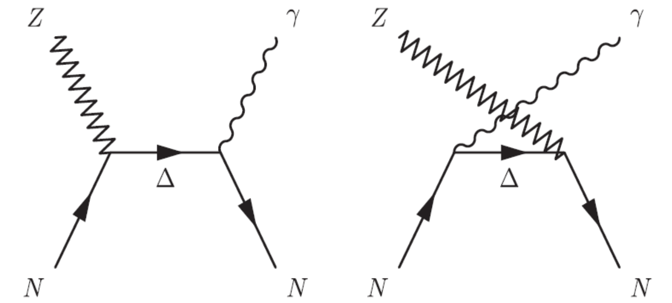



FIG. 3. Production of photons through the $\Delta$ resonance.

# NC photon production

- more and recent work on this:
"Weak Pion and Photon Production off Nucleons in a Chiral Effective Field Theory", B. Serot, X. Zhang, arXiv:1011.5913 [nucl-th]
- related to and constrained by $\pi$ production
- antineutrino predictions also

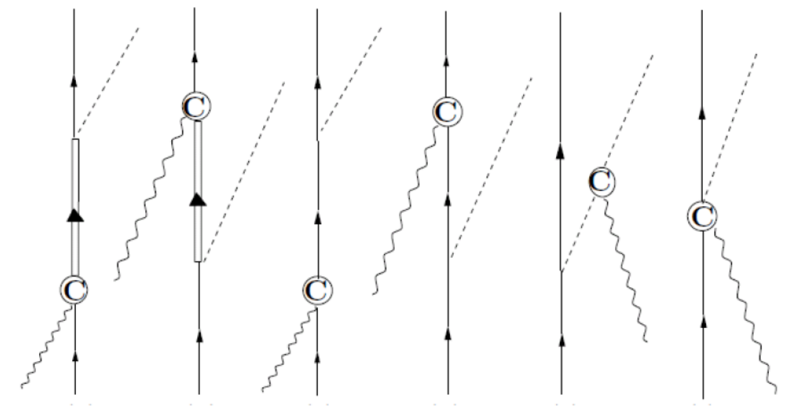


Fig.1: Feymann diagrams for pion production. Change the outgoing pion line to photon line for photon production. C indicates both vector and axial vector currents.

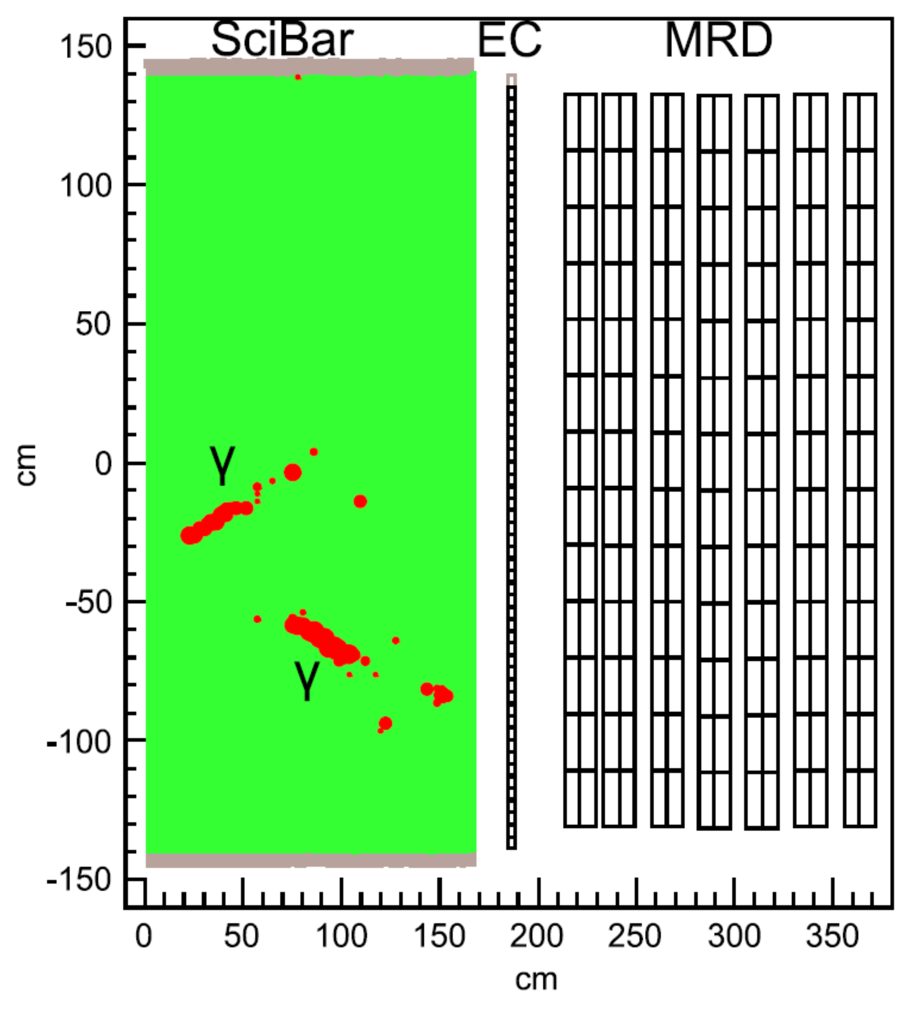
| $E_{QE}$(GeV) | [0.2 , 0.3] | [0.3 , 0.475] | [0.475 , 1.25] |
|---|---|---|---|
| coh | 3.1 | 10.37 | 5.59 |
| incoh | $6 \times (1.01 + 1.01)$ | $6 \times (3.64 + 3.62)$ | $6 \times (2.90 + 2.88)$ |
| total | 15.22 | 53.93 | 40.27 |
| MiniBN | 19.5 | 47.5 | 19.4 |

Tab.1: NC photon production event's EQE distribution in MiniBooNE for neutrino scattering.

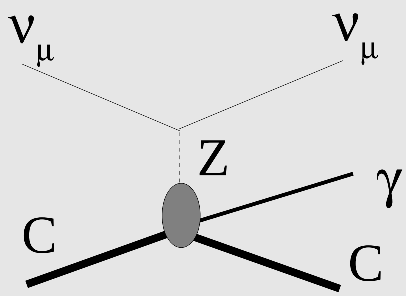
# Measuring NC photon production

- a measurement is accessible in SciNOvA (along with important NC $\pi^0$ channel)

NC$\pi^0$ event in scibar/SciBooNE

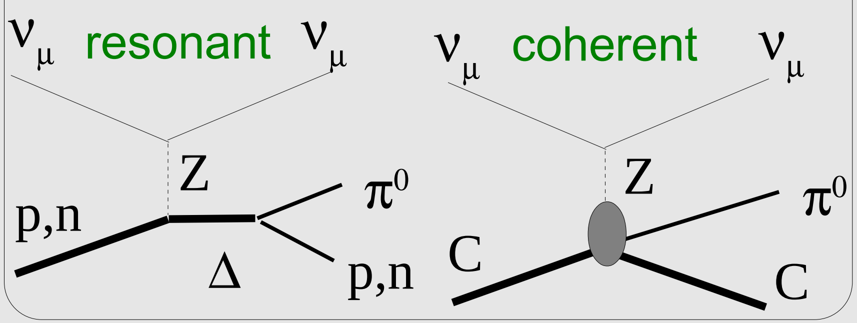



$$\nu_\mu C \rightarrow \nu_\mu C \gamma$$




NC $\gamma$ production

$$\nu_\mu (p,n) \rightarrow \nu_\mu (p,n) \pi^0, \pi^0 \rightarrow \gamma\gamma$$




NC$\pi^0$ production

# Measuring NC photon production

- SciNOvA event rates
- ~ equal to full MiniBooNE neutrino sample (but in 10 tons).
- NC$\gamma$ cross sections are calculated to be O($10^{-3}$) that of CCQE (from Hill or Serot/Zhang)
- resulting in sample of O(100) events in MB (same as 0.1% oscillations)
- SciNOvA will collect O(100) events of this type if calculations are correct
- photon recon down to ~100MeV and comparison with NC$\pi^0$ channel allows a measurement of NC$\gamma$
- together with NC$\pi^0$ channel will lend crucial info to $\nu_e$ appearance search (NOvA and others)

SciNOvA $\nu$ kevent/yr (6E20POT) in 10 ton fiducial vol

| | Charged-current | Neutral-current |
|---|---|---|
| elastic | 220 | 86 |
| resonant | 327 | 115 |
| DIS | 289 | 96 |
| coherent | 8 | 5 |
| total | 845 | 302 |
| $\nu + A \rightarrow \pi^0 + X$ | 204 | 106 |

photon energy in NC$\pi^0$ event in scibar/SciBooNE

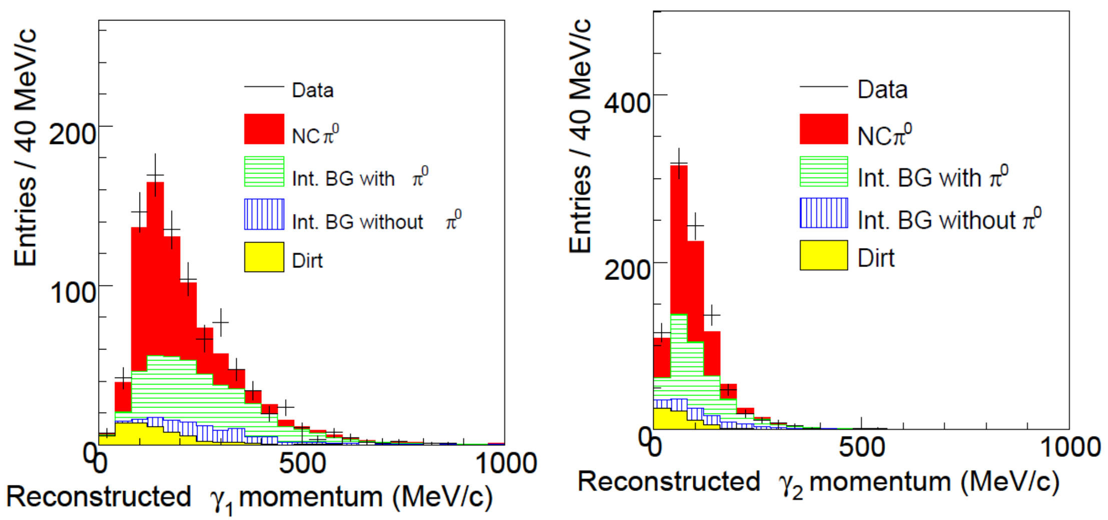


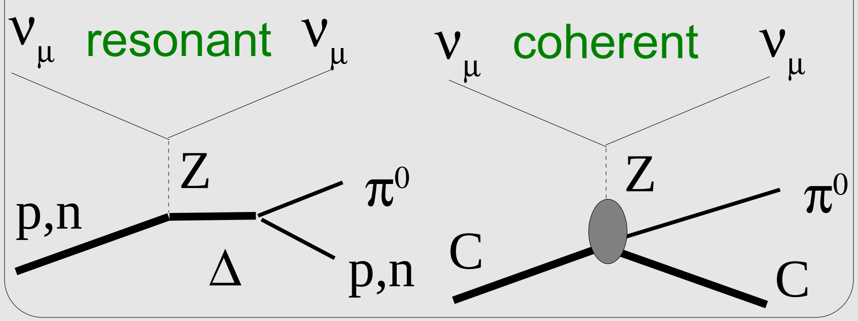

Figure 6.4: $E^{rec}_{\gamma 1}$ and $E^{rec}_{\gamma 2}$ before the $\pi^0$ mass cut ($E^{rec}_{\gamma 1} > E^{rec}_{\gamma 2}$)

# More neutrino scattering channels

Other neutrino scattering channels
to be measured with SciNOvA:

- $\nu_\mu$ NC production of neutral pions
  - very important oscillation background
  - sizeable coherent production?
  - narrow band beam offers lower background from higher energies

$$\nu_\mu(p,n)\rightarrow\nu_\mu(p,n)\pi^0,\pi^0\rightarrow\gamma\gamma$$

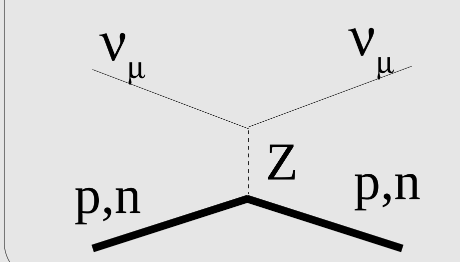



NCπ⁰ production

- $\nu_\mu$ neutral-current (NC) elastic (NCel)
  - important complementary channel to CCQE
  - extra contributions to axial form factor from strange quarks?

- $\nu_\mu$ CC production of $\pi^+$, $\pi^0$
  - insight into models of neutrino pion production via nucleon resonances

$$\nu_\mu(p,n)\rightarrow\nu_\mu(p,n)$$




NC elastic

# Application to NOvA

NOvA will conduct $\nu_e$ and $\overline{\nu}_e$ appearance search to probe $\theta_{13}$, mass hierarchy, CP phase $\delta$

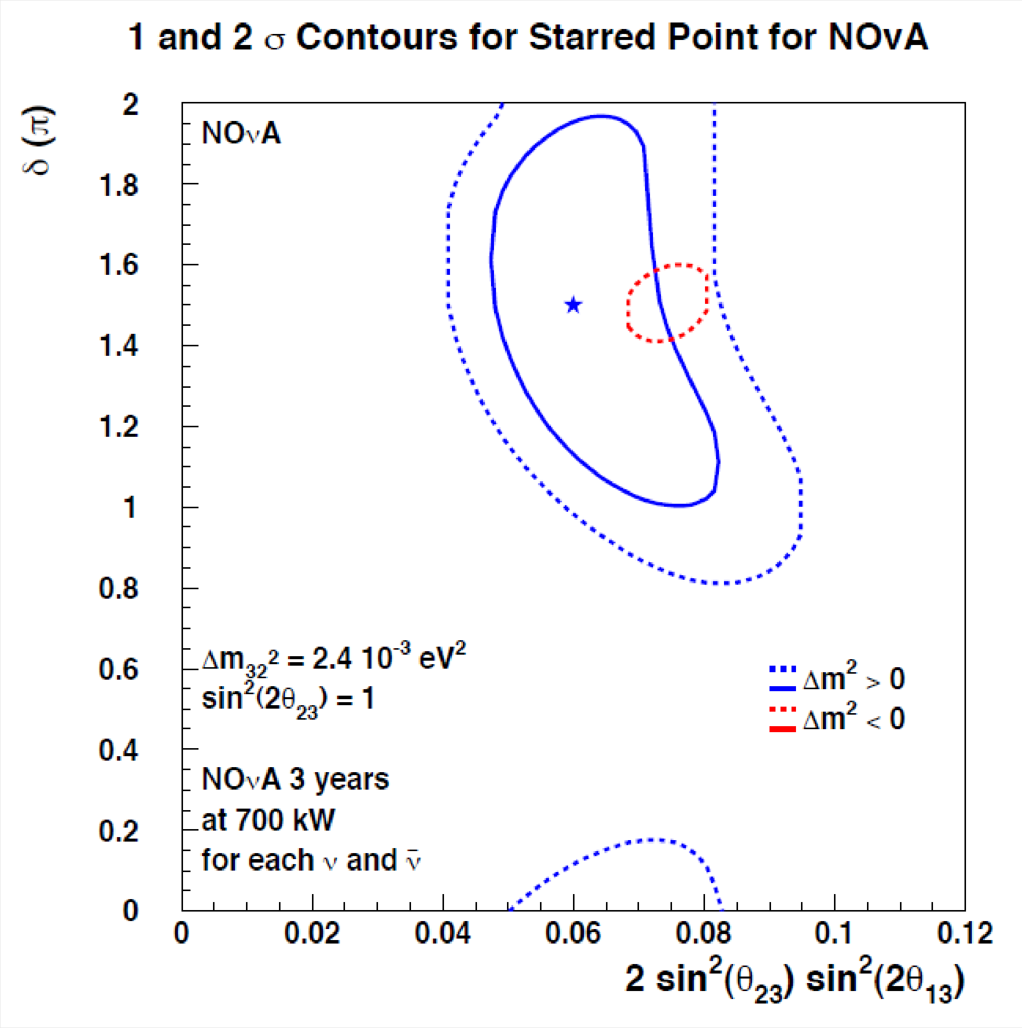
- Among most important questions in neutrino and particle physics today and central in FNAL intensity-frontier program.

- $\sin^2\theta_{13}$ sensitivity down to 0.01 at 90% CL

- with estimated $\nu_e$ efficiency ~35% and NC, $\nu_\mu$ CC background mis-ID probabilities ~ 0.4%, 0.1%

- Any additional tests of these numbers will be extremely valuable for NOvA

- The fine-grained SciNOvA detector can provide this.



# Application to NOvA

- A double-scan method comparing SciNOvA and NOvA-near can provide signal efficiency and background misID probabilities.

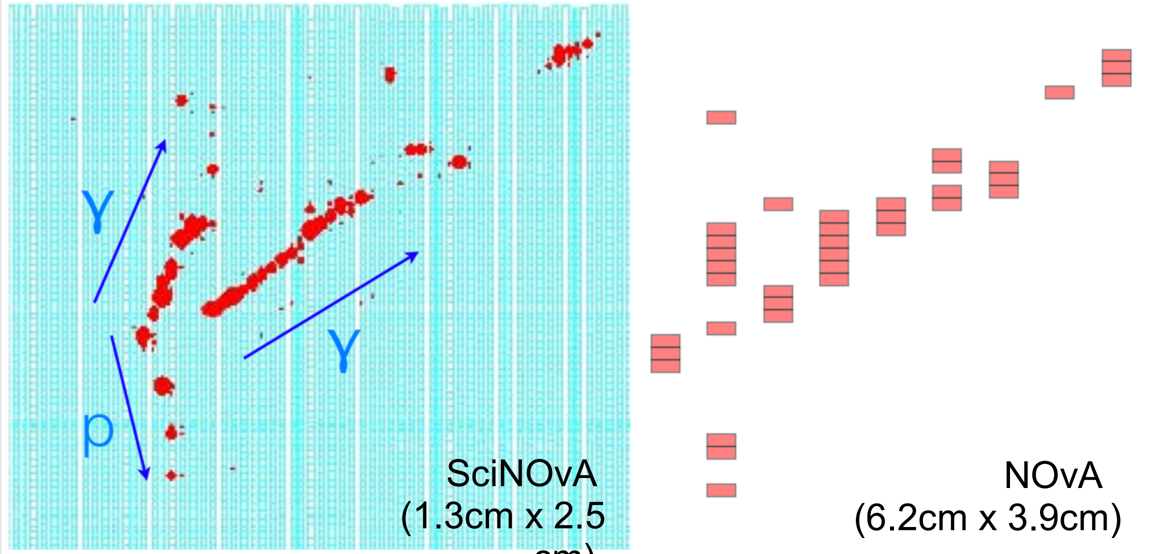
- ala bubble chamber double-scans to measure scanner efficiencies

Method:
- Classify events labeled as signal/bckgd in SciNOvA compared to those resampled with larger pixel size (as NOvA) Nss, Nsb, Nbs, Nbb

- can then determine NOvA efficiency, $\varepsilon_N$ and NOvA, SciNOvA misID probabilities: $\gamma_N$, $\gamma_{SN}$

- results in a <3% (relative error) cross check of $\varepsilon_N$ , $\gamma_N$, $\gamma_{SN}$ at 3σ.

- a sensitive cross check!




p + π$^0$ in SciBar

Same event resampled in NOvA

test case simulated event totals in 1-yr SciNOvA running

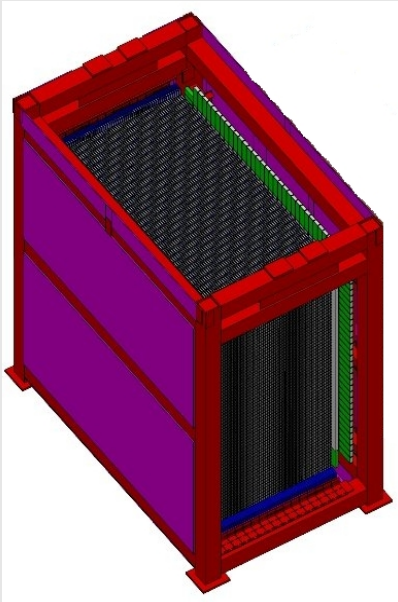
| | $N_{ss}$ | $N_{sb}$ | $N_{bs}$ | $N_{bb}$ | $\chi^2$ |
|---|---|---|---|---|---|
| Nominal | 15500 | 50300 | 66600 | 10867600 | - |
| $\gamma_N$ higher by 10% | - | - | +4300 | -4300 | 279 |
| $\gamma_N$ and $\gamma_{SB}$ higher by 10% | - | +2200 | +4300 | -6500 | 371 |
| $B$ higher by 10% | -1500 | -2800 | -2300 | +6600 | 403 |

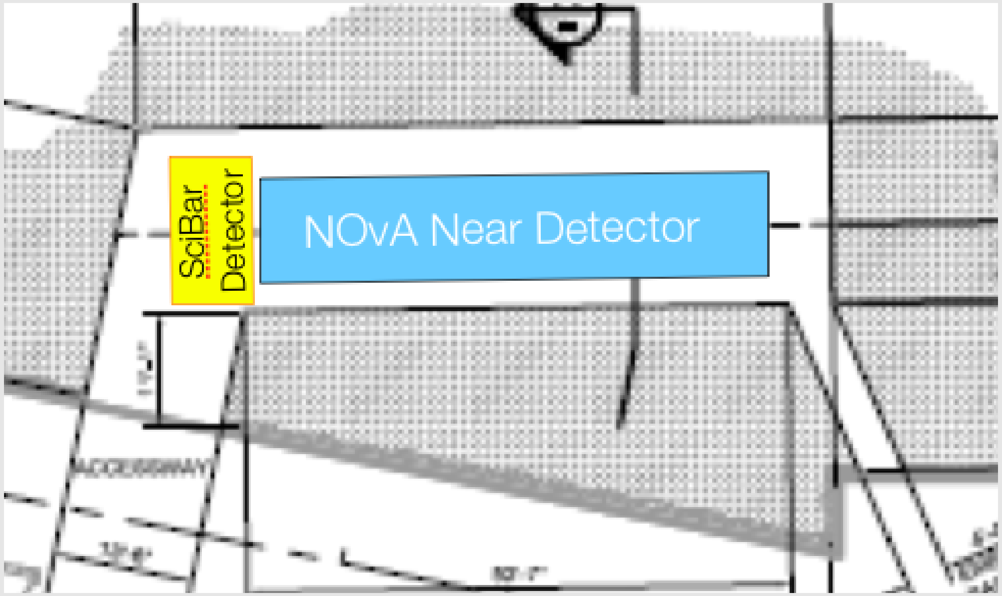
# SciNOvA current status

- Presented to FNAL PAC, 11/10 - recommended that NOvA consider SciNOvA

- The NOvA collaboration supports the SciNOvA physics case and is seriously evaluating it as a possibility. Study group consisting of NOvA and non-NOvA physicists recently formed to answer remaining technical questions.

- Final decision by NOvA hinges on:
    - People power
    - Earned contingency. Maybe ~1 year before NOvA knows if it has earned enough contingency to complete SciNOvA

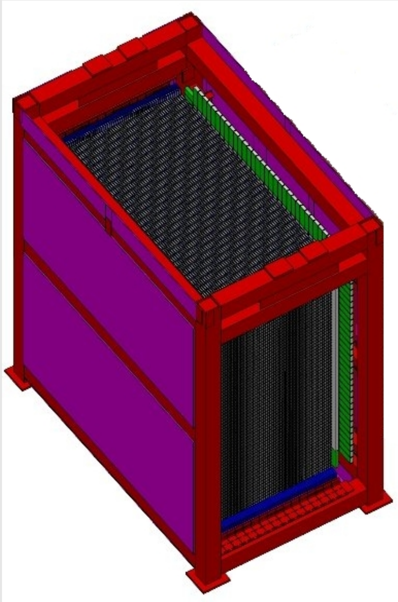


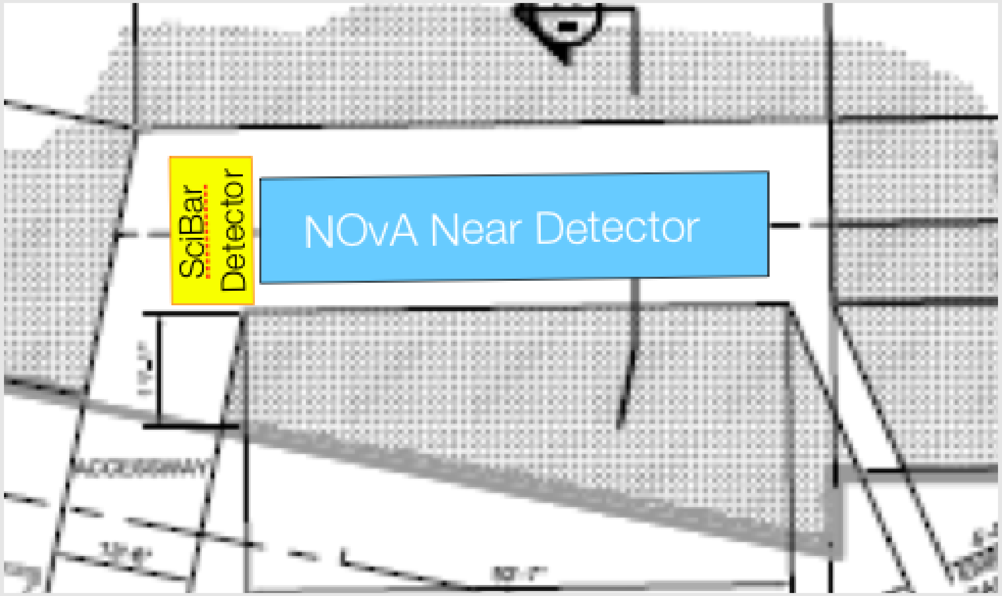


# Conclusions

- The addition of the SciNOvA detector to the NOvA near detector in the narrow-band beam would increase the NOvA physics program substantially for modest investment.

- This will allow:
  - new insight into neutrino scattering, particularly follow-up on the interesting and unexplained MiniBooNE neutrino cross section results.
  - important cross checks of backgrounds for the flagship NOvA $\nu$ oscillation program.





extra slides

# SciNOvA: costs

Total project costs:

- FNAL costs:
  - those involved with scibar support structure, rigging, underground installation.
  - costs based on recent SciBooNE/SciBar experience

- scint extrusions costs estimate from A. Pla-Dalmau

- all labor, engineering, DAQ programming (excluding physicists) included

- Intend to seek outside funding for non-FNAL costs

- Total: $2.41M

SciNOvA project cost estimate

| Item | costs ($) | totals($) | est FNAL costs ($) |
|---|---|---|---|
| **scibar** | | **804818** | |
| extrusions: 15k 3m strips, 2.5cmx1.3cm | 410218 | | |
| WLS fiber: 48km@$2/m | 192000 | | |
| fiber/PMT cookie assemblies | 25000 | | |
| fabricate new scibar cradle | 120000 | | 120000 |
| HVAC system | 8000 | | 8000 |
| material and fab for assembly, lifting jigs | 24000 | | 24000 |
| labor: assembly rigging | 25600 | | 25600 |
| **IRMs** | | **1465770** | |
| assembled boards: 250 | 1106028 | | |
| clock board system | 3380 | | |
| IRM power system | 26212 | | |
| DAQ computer/enet hardware | 40000 | | |
| elec design/testing/debug for IRMs | 87900 | | |
| mechanical design for IRMs | 58600 | | |
| final board assembly, repair | 37400 | | |
| DAQ firmware, software | 106250 | | |
| **detector installation** | | **141800** | |
| engineering | 51200 | | 51200 |
| rigging | 25600 | | 25600 |
| material and fab for installation, lifting jig | 30000 | | 30000 |
| misc underground infrastructure | 35000 | | 35000 |
| **project total** | | **2412389** | 319400 |

# SciNOvA: costs

**IRM readout board cost breakdown**

| IRM component | qty | costs each | total |
|---|---|---|---|
| assembled PCB with components | 250 | $2,515.00 | $628,750 |
| integrated HV supply | 250 | $32.63 | $8,158 |
| MAPMTs | 250 | $1,600.00 | $400,000 |
| PMT base PCB assembly | 250 | $95.00 | $23,750 |
| PMT mounting parts, ribbon cable | 250 | $142.84 | $35,710 |
| chasis mounting parts, connectors | 250 | $15.71 | $3,928 |
| Fans | 250 | $22.93 | $5,733 |
| total IRM costs | | | **$1,106,028** |
| cost/board | | | $4,424 |
| cost/channel | | | $69.13 |

- Total: ~$2.4M

**SciBar scintillator extrusions cost estimate**

## COST ESTIMATE FOR SCINOVA

Requested by Mark Messier at Indiana University
Prepared by Anna Pla-Dalmau
Date: May 13, 2010

IMPORTANT: PROJECT WILL BE BILLED AT ACTUAL COSTS. THIS IS AN ESTIMATE.

Scintillator bars with titanium dioxide coating with one hole for a WLS fiber: 2.5 cm x 1.3 cm at 300 cm
Total amount of scintillator: 36,000 m (12,000 strips)

| | Estimated Materials and Services Cost ($) | Estimated Time (hours) | Rate (hours) | Estimated Labor Cost ($) | Total Estimated Cost Materials and Labor ($) |
|---|---|---|---|---|---|
| ***R&D Material*** | | | | | |
| Die | $10,000.00 | | | | |
| Polystyrene pellets (1,480 Kg @ $2.65 each) | $3,922.00 | | | | |
| Dopants (34 bottles @ $190 each) | $6,460.00 | | | | |
| Titanium dioxide pellets (40 Kg @ $7.85 each) | $314.00 | | | | |
| Nitrogen gas (10 $LN_2$ dewars @ $126 each) | $1,260.00 | | | | |
| Consumables (jars, labels, QC tools,…) | $1,000.00 | | | | |
| ***R&D Labor*** | | | | | |
| Extrusion preparation and operation | | 120 | $60.00 | $7,200.00 | |
| Extrusion assistance | $3,400.00 | 100 | $34.00 | | |
| Extrusion assistance and QC | | 60 | $35.00 | $2,100.00 | |
| Set-up and tear-down (half-day each, 2 people) | | 20 | $60.00 | $1,200.00 | |
| ***Production Material*** | | | | | |
| Polystyrene pellets (14,800 Kg @ $2.65 each) | $39,220.00 | | | | |
| Dopants (340 bottles @ $190 each) | $64,600.00 | | | | |
| Titanium dioxide pellets (400 Kg @ $7.85 each) | $3,140.00 | | | | |
| Nitrogen gas (50 $LN_2$ dewars @ $126 each) | $6,300.00 | | | | |
| Consumables (jars, labels, QC tools,…) | $1,500.00 | | | | |
| ***Production Labor*** | | | | | |
| Extrusion preparation and operation | | 800 | $60.00 | $48,000.00 | |
| Extrusion assistance | $14,960.00 | 440 | $34.00 | | |
| Extrusion assistance and QC | | 400 | $35.00 | $14,000.00 | |
| Project coordination | | 80 | $65.00 | $5,200.00 | |
| Set-up and tear-down (half-day each, 2 people) | | 20 | $60.00 | $1,200.00 | |
| ***Crating and Shipping*** | | | | | |
| Crate - 12 wooden crates | $3,600.00 | | | $3,600.00 | |
| Shipping* | $6,000.00 | | | | |
| ***Extrusion Equipment Maintenance*** | $3,000.00 | | | | |
| Estimated Direct Cost | $168,676.00 | | | $82,500.00 | $251,176.00 |
| FNAL Indirect Charges (14.4% M&S) | $24,289.34 | | | | $24,289.34 |
| FNAL Indirect Charges (63.89% Labor) | | | | $52,709.25 | $52,709.25 |
| TOTAL Estimated Cost | | | | | $328,174.59 |

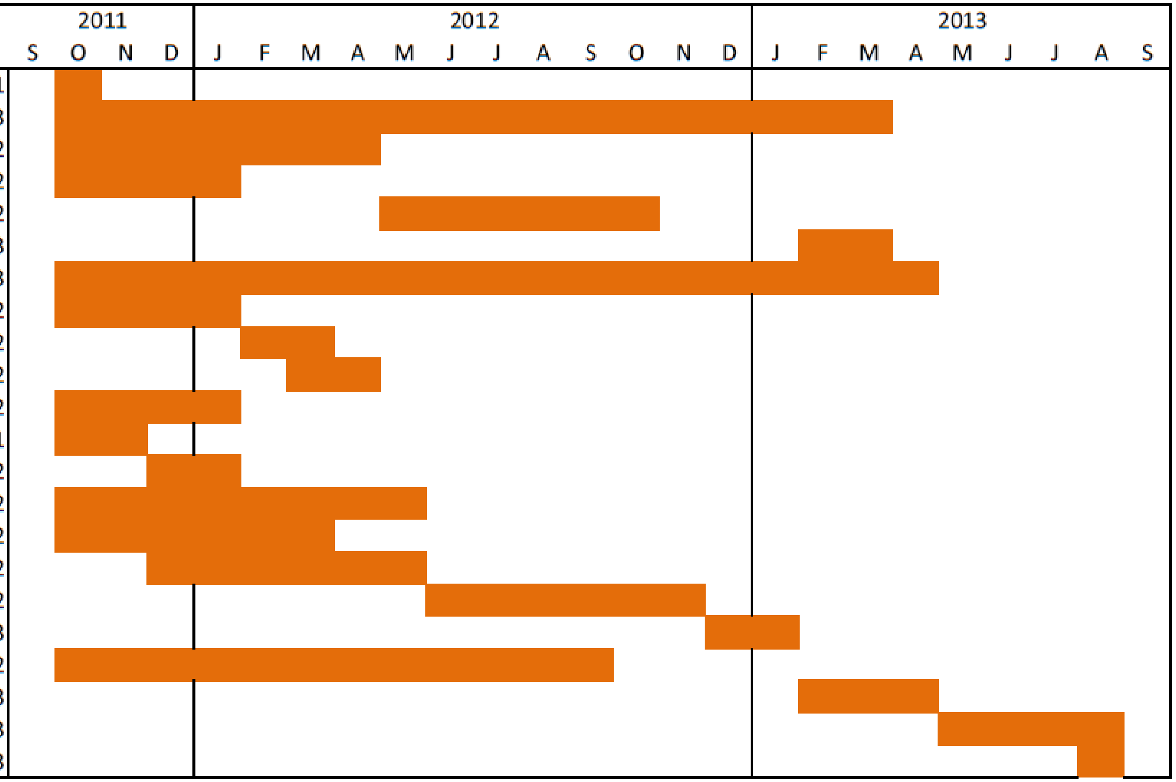
*This is an estimate.

# SciNOvA: schedule

SciNOvA project schedule:

- assumed start in Fall '11, ready Aug '13 (23mos)
- SciBar extruded, assembled at FNAL
- readout board, PMT, fiber interface work at collaborating institutions and with vendors

| task | duration (days) | start | end |
|---|---|---|---|
| start of project | 0 | 10/01/11 | 10/01/11 |
| scibar | 0 | 10/01/11 | 03/14/13 |
| manufacture scintillator | 200 | 10/01/11 | 04/18/12 |
| fabricate cradle | 120 | 10/01/11 | 01/29/12 |
| assemble scibar | 180 | 04/18/12 | 10/15/12 |
| install in tunnel | 60 | 01/13/13 | 03/14/13 |
| IRM (readout boards) | | 10/01/11 | 04/23/13 |
| update PCB design | 100 | 10/01/11 | 01/09/12 |
| PCB procurement/assembly | 60 | 01/09/12 | 03/09/12 |
| testing | 60 | 02/08/12 | 04/08/12 |
| IRM-PMT interface | | 10/01/11 | 01/29/12 |
| design | 60 | 10/01/11 | 11/30/11 |
| manufacture | 60 | 11/30/11 | 01/29/12 |
| PMTs | | 10/01/11 | 05/28/12 |
| procurement | 180 | 10/01/11 | 03/29/12 |
| testing | 180 | 11/30/11 | 05/28/12 |
| PMT module assembly | 180 | 05/28/12 | 11/24/12 |
| full module assembly | 60 | 11/24/12 | 01/23/13 |
| firmware/software development | 360 | 10/01/11 | 09/25/12 |
| install system in tunnel | 90 | 01/23/13 | 04/23/13 |
| commissioning | 120 | 04/23/13 | 08/21/13 |
| project ready | 0 | 08/21/13 | 08/21/13 |



# Science case: CCQE scattering

Estimated errors on MiniBooNE CCQE total cross section measurement

- check of method with MiniBooNE
- underestimates error slightly off flux peak due to naive treatment of flux error